A BATTERY POWERED, 200-KW RAPID CAPACITOR CHARGER FOR A PORTABLE RAILGUN IN BURST MODE OPERATION AT 3 RPS [*]

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Abstract

A portable power supply is being developed to rapidly charge the capacitor bank of a low velocity railgun system for countermeasure deployment from aircraft and watercraft. The goal is charge a 15-mF capacitor bank to 2.3 kV in 200 ms to allow countermeasure deployment in bursts of several rounds at a rate of 3 RPS (rounds per second). Due to possible use aboard aircraft, components where chosen to minimize weight and volume. For this reason, as well as for simplicity and to reduce cost, a series bank of special, high-current lead-acid batteries was chosen as the source of prime power. The 192-V voltage of the battery bank is boosted to 2 kV using a bridge converter comprised of four IGBT switches in an H-bridge configuration, a ferrite-core step-up transformer, and a full wave rectifier.

I. INTRODUCTION

A small, low-velocity railgun is being developed at NRL for a new, electrically-driven countermeasure deployment system [1]. In order for this railgun to fire in a burst mode at 3 RPS, a rapid capacitor charger is required. The initial specifications required the rapid charger to charge the 15-mF capacitor bank to 2.3 kV in 200 ms. This requires the rapid charger to deliver an average power of about 200 kW during the charge pulse to transfer the 40 kJ to the capacitor bank. Recently, improvements in the railgun have reduced the required capacitor voltage to 2.0 kV. This reduces the required power to 150 kW and energy to 30 kJ. However, because of the modular approach to the charger design, described later, either of these goals could be met with the current design.

The application to military aircraft use puts several conditions on the rapid charger. It must be self-contained and capable of firing many shots and therefore has to be driven by a battery bank. The battery bank has to be safe for aircraft use and operate in any orientation. Also, it is very desirable to minimize volume and also weight.

II. PREVIOUS WORK

The current design of the rapid charger is based on previous work developing a battery bank that heated up to 12-in. square by 4-mil thick sheets of Ta (tantalum) foil to near-melt temperatures (~2600 K) in vacuum with precisely controlled pulse widths from ~200 to 1000 ms [2]. This Ta heater is portable, mounted on a metal cart, and is entirely self-contained with an integral control system. A photo of the Ta heater cart is shown in Fig. 1. The Ta heater puts out a sustained ~160 kW, once the foil temperature stabilizes (~100 ms). The initial current, more that 6 kA, drops to ~4 kA once the foil is heated. The system consists of three identical modules that are connected in parallel at the Ta foil.

Figure 1. Photo of the Ta heater cart.

Many of the design concepts and similar components are used in the rapid charger. The same modular approach is used as multiple identical modules can be connected at the capacitor bank. Similar “dry cell” lead-acid batteries are used. The same contactors are to be used to separate the bank into low voltage, 50 V, segments for safety when not being used. The two, single IGBT modules used in parallel by each module of the Ta

[*] Work supported in part by the US Dept of Agriculture under contract number DOA-8910

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
JUN 2007	**N/A**	**-**

4. TITLE AND SUBTITLE
A Battery Powered, 200-Kw Rapid Capacitor Charger For A Portable Railgun In Burst Mode Operation At 3 Rps

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Plasma Physics Division Naval Research Laboratory Washington, DC 20375 USA

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. IEEE International Pulsed Power Conference (19th). Held in San Francisco, CA on 16-21 June 2013., The original document contains color images.

14. ABSTRACT
A portable power supply is being developed to rapidly charge the capacitor bank of a low velocity railgun system for countermeasure deployment from aircraft and watercraft. The goal is charge a 15-mF capacitor bank to 2.3 kV in 200 ms to allow countermeasure deployment in bursts of several rounds at a rate of 3 RPS (rounds per second). Due to possible use aboard aircraft, components where chosen to minimize weight and volume. For this reason, as well as for simplicity and to reduce cost, a series bank of special, high-current lead-acid batteries was chosen as the source of prime power. The 192-V voltage of the battery bank is boosted to 2 kV using a bridge converter comprised of four IGBT switches in an Hbridge configuration, a ferrite-core step-up transformer, and a full wave rectifier.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**SAR**	**5**	

heater cart are replaced by similar dual-IGBT modules in an H-bridge configuration. The same IGBT driver boards are also used (although they could be replaced by more compact, dual-driver modules).

III. RAPID CHARGER DESIGN

As mentioned earlier, a modular approach is used since multiple modules can be bussed together to achieve the desired output power. Since the railgun is actually designed as two separate banks of 7.5 mF each, it is convenient to have a two module system with each module charging 7.5 mF. This also adds a level of robustness to the system since, in the event of a failure, a single module could still charge the whole bank, but at half the rate.

The major components of the rapid charger module are the battery bank and the H-bridge converter. The H-bridge converter consists of four IGBT switches, a transformer, and a bridge rectifier.

A. Battery Bank Design

The rapid charger uses the same brand of "dry cell" lead-acid batteries previously used in the Ta heater cart, but in a smaller size. These batteries are commercially available and are sold in the same package as regular lead-acid batteries. However, the acid in these batteries is trapped in a jelly roll of glass fiber and lead sheet. So, the acid cannot leak, even if cut open. The most important feature of these batteries is the short-circuit current, which is twice that of conventional battery of the same size. Also, these batteries do not explode or catch fire when short-circuited. They are labeled as "Nonspillable" and are safe for air transport without DOT hazard labeling. Additionally, they are "deep cycle" batteries so they can be completely drained and still recover. Also, they have a longer shelf life than conventional batteries. The stored energy in these batteries is on the order of a MJ and so the system should be able to fire ~1000 rounds without being recharged.

It is known from previous work that the source impedance of the batteries can be determined by the specified short-circuit currents, I_{SC}, and open-circuit voltage, V_{OC}. From this, one can calculate the maximum output power assuming a matched load,

$$P_{Max} = V_{OC} \cdot I_{SC} / 4 . \qquad (1)$$

P_{Max} for the whole bank is just the sum over all the bank batteries. For the Ta heater cart, P_{Max} was 195 kW and the actual power delivered to a closely matched load was about 160 kW. So, 82% of P_{Max} was coupled to the load. Keeping in mind that this was a simple DC connection between source and load, this percentage is taken as the limit of what is reasonably expected for the rapid charger where additional power conditioning is required.

A smaller size battery (motorcycle size) was used for this application than was used for the Ta heater (car size) in order to minimize battery bank volume. From a plot of P_{Max}/Volume for one particular product line of increasing sized batteries, shown in Fig. 2, a mid-size battery (designated PC680 by the manufacturer) delivers the most power per unit volume at 5.9 kW for 151 cu. inches. The rated short-circuit current for this battery is 1.8 kA. The battery voltage used in calculations is 13 V instead of the given 12 V based on actual measurements of a fully charged battery. This battery is also next to the peak in terms of power per unit weight. Note that one could achieve 2.0 kV and the required power by putting many of the smallest battery in series, but the total volume of battery required would be about 4 times greater. Plus, there are other issues with so many cells in series having to do with balancing and charging.

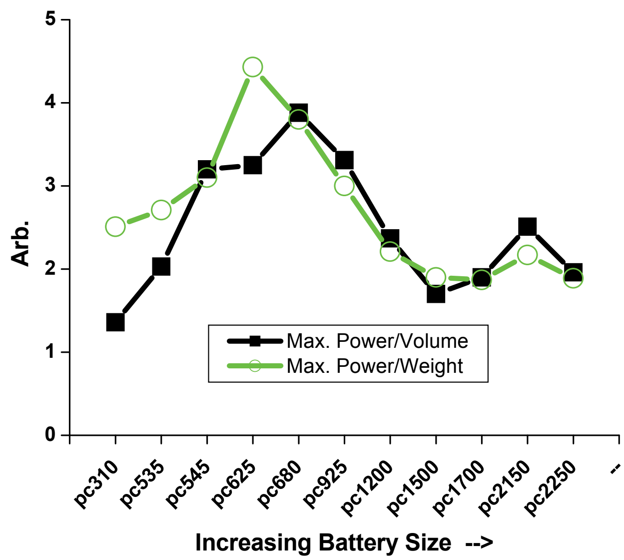

Figure 2. Plot of P_{Max}/volume and P_{Max}/weight of batteries of increasing physical size.

Figure 3. Photo of the 16 PC680 battery bank of the test module.

Assuming a two module system, each module must deliver an average 75 kW. Assuming the maximum

efficiency of 82% described earlier, each module requires at least 16 batteries. So, the current module battery bank design uses 16 PC680 batteries with a volume of 1.4 cu. feet and a weight of 246 lbs. A photo of the battery bank of the test module is shown in Fig. 3. A fuse is installed in case of catastrophic failure although its resistance does cause some inherent loss. Switches are used to isolate the bank into four, 50-Volt segments for safety purposes.

B. H-Bridge Converter Design

Because the voltage of the 16 PC680 module battery bank is only about 200 V, a DC-DC converter is required to step up the voltage a factor of 10 to 2.0 kV. An H-bridge converter topology was selected as it is believed that this provides the highest power per volume. The H-bridge converter consists of four IGBT switches, a transformer and a full-wave rectifier. A general diagram of the circuit is shown in Fig. 4. With switches 1 and 4 on and 2 and 3 off, current flows in one direction through the transformer. When reversed, current flows the other way through the transformer. By switching at a high frequency (kHz range), a small transformer can be used.

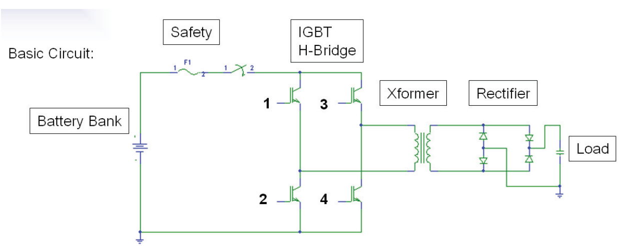

Figure 4. Basic circuit diagram of the H-bridge converter.

C. IGBT Switches

IGBT module switches were used for their high current and voltage ratings, fast switching speeds, and low driving requirements. These IGBT modules are very similar to the ones used in the Ta heater except for a higher, 1200 V, voltage rating and packaging as dual IGBT modules. A higher voltage rating is required because of the inductive voltage spike that occurs when switching. A snubber capacitor is used to reduce this voltage, but this is more difficult at higher switch currents and frequencies.

A nice feature of dual IGBT modules is that the internal free-wheeling diodes in the module can be used to do the snubbing simply by attaching a capacitor across two of the three terminals. Capacitors, 3.0 uF each, designed just for this purpose were used. A photo of the IGBT modules and snubbers is shown in Fig. 5.

IGBT driver boards from the IGBT module vendor were used to supply optically isolated voltages to bias the IGBTs on and off. The test module uses four individual driver boards, the same ones used for the Ta heater, although dual driver boards are available.

D. Transformer

The transformer is probably the most complex component of the H-bridge converter to design. Design is complicated by core loss, winding resistance, leakage inductance and stray capacitances. Although an ideal transformer keeps the flux in the core at zero, in practice the core flux increases during a voltage pulse due to imperfect coupling. Eventually the core will saturate, decoupling the primary and secondary inductances, something that must be avoided.

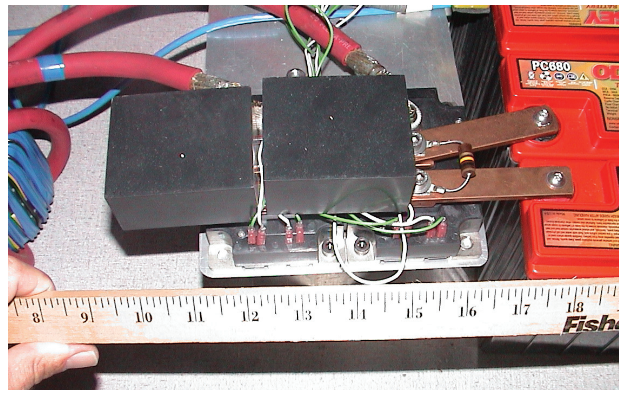

Figure 5. Photo of the two H-bridge dual-IGBT modules and their snubber capacitors.

For this application a rather large core is required. This is because large diameter wires are required to handle the ~1000 A primary and ~100 A secondary currents. This limits the number of turns possible which leads to a large voltage per turn that, along with the switching frequency, determines the Volt-seconds of core material required. The upper switching frequency is currently limited by the IGBT switches to the 10 kHz range. No commercially available transformer of the size required could be located so one was wound in-house using 107 mm OD toroidal ferrite cores.

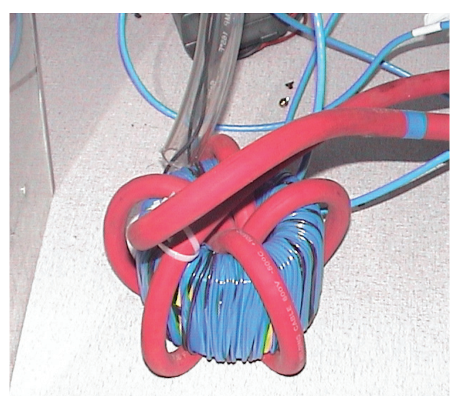

Figure 6. A photo of the transformer used in the test module DC-DC converter.

Several windings were tried and eventually a core consisting of four of the 18 mm tall, type 3F3 ferrite toroids stacked atop one another was used. The best windings were found to be 5 primary turns of AWG 2/0 high-flex copper cable and 60 secondary turns of AWG 14 single conductor copper cable for a 12:1 turns ratio. A photo of the transformer used in the test module is shown in Fig. 6. It was found that this larger than the required 10:1 turns ratio was better as the ultimate voltage is approached in a tangential manner. Now that the approximate switching frequency and windings are known, a better transformer design is possible.

E. Rectifier

A full-wave bridge rectifier is used to convert the high-voltage AC power from the transformer back to DC to charge the railgun capacitors. The high switch frequency requires fast-recovery diodes. No module could be found commercially that can handle the ~150 A, 2400 V requirements, so the bridge was constructed of 24 ultrafast-recovery diodes rated at 75 A, 1200 V in series-parallel combination to meet the requirement.

IV. TEST MODULE RESULTS

A test module was constructed to demonstrate the feasibility of the rapid charger design described earlier. The ideal system would consist of two modules, each charging one of the 7.5 mF capacitor banks to 2.0 kV in 200 ms. Test results described below show that three modules would currently be required to meet these goals. However, methods will be described whereby the two of these modules could still achieve overall goals.

The test module, comprising the 16 battery bank and the DC-DC converter described earlier, was assembled and tested into 2, 4, and 8-mF capacitor loads. Other components of the test setup, shown in Fig. 7, included a trigger generator for IGBT switch timing, a trigger amplifier circuit, a dump resistor, diagnostics and a battery charger.

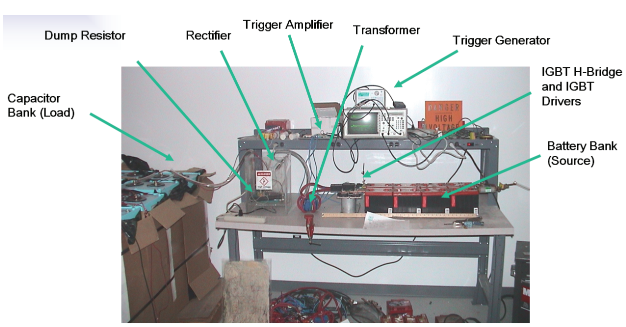

Figure 7. A photo of the test setup for the rapid charger module with major components labeled.

The test module timing was varied over a range of frequencies. It was found that the minimum usable frequency was 4.5 kHz. Below this the average output power dropped due to core saturation as the output voltage approached 2 kV. This was indicated by a sharp increase in primary current at the end of each pulse. The maximum switch frequency was found to be 9.1 kHz. Attempts to switch faster resulted in IGBT failures, most likely due to overheating at the beginning of the charge cycle when IGBT currents are high and so switching losses are at their highest.

By charging in many 4.4 ms bursts from the trigger generator, instantaneous output powers (the average power during the burst) can be calculated as well as the average output power (the time average of the instantaneous power). At 4.5 kHz the average output power of the test module was 36.8 kW. At 9.1 kHz this increased to 50.7 kW, which is 68% of the 75 kW goal.

Plots of instantaneous output power versus load voltage were useful for optimizing the system. It was observed that the output power drops off sharply toward the end of the charge cycle. The primary current also drops from close to short-circuit battery current at the beginning of the charge cycle to very low values toward the end. From an equivalent circuit perspective, the effective load impedance begins very low and then increases. The effective load impedance becomes close to matched in the middle of the charge cycle where instantaneous power peaks.

In order to provide a better impedance match to the source, a second, identical, DC-DC converter was placed in parallel to the first. As shown in the plots of Fig. 8 (data taken with a 4.2 mF load), the twin converters increased the output power over the entire charge cycle. At 4.5 kHz, the average power increased 40% to 53 kW and at 9.1 kHz, the average power increased 15% to 58 kW, which is 78% of the 75 kW goal. The second DC-DC converter also has the benefit of reducing the peak IGBT current below the rated value of 1200 A (600 A average), although it is known that the rated values can be exceeded for short times as long as the IGBT module doesn't overheat. The second converter also adds an extra layer of redundancy since the module will still work, although at a reduced level, even if one of the IGBT switches should fail.

The 58 kW average output power of the test module at 9.1 kHz requires was found to be independent of the load capacitance. Tests with different capacitance loads all show the same instantaneous power vs. load voltage curve. The measured charge times to 2.0 kV were 75, 150 and 300 ms for 2.1, 4.2 and 8.4 mF loads. The measured voltage versus time for each of these loads is shown in Fig. 9. Based on these measurements, the test module would need 268 ms to reach 2.0 kV with the target capacitance of 7.5 mF.

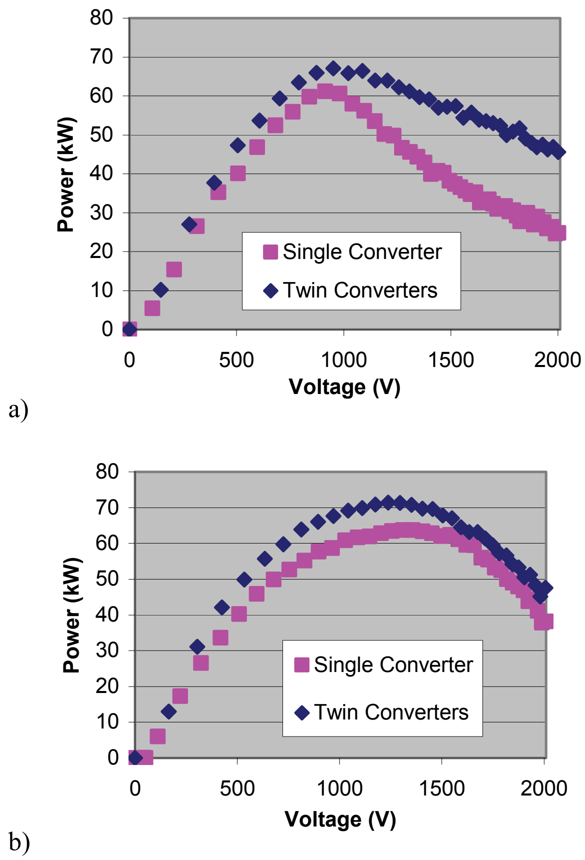

Figure 8. Measured instantaneous output power of the test module with a switching frequency of a) 4.5 kHz and b) 9.1 kHz, both with single and twin DC-DC converters.

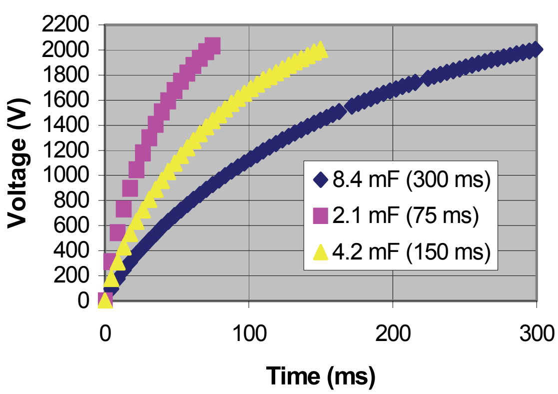

Figure 9. Measured capacitor load voltage during test module charging of three different load capacitances.

V. SUMMARY

A rapid capacitor charger for a small railgun system to operate in a burst mode at 3 RPS has been designed based largely on previous work with a Ta heater cart. The design incorporates many features of the Ta heater cart including the dry-cell battery and IGBT switch technologies and the modular design. A test module with a bank of 16 mid-sized batteries, with the most power per unit volume, was constructed. A DC-DC converter based on four IGBT switch modules in an H-bridge configuration to drive a step-up transformer and bridge rectifier completed the test module.

Testing of one module showed a significant increase in output power could be achieved by simply adding a second DC-DC converter in parallel to the first. The second converter also increases the robustness of the system. An average output power of 58 kW was demonstrated from the test module and found to independent of the actual capacitance being charged. The weight and volume of the complete system is dominated by the batteries. The batteries of the module weigh 246 lbs. and have a volume of 1.4 cu. ft. With the current design, three modules would be required to meet the 150 kW average output power requirement. However, there may be ways to achieve the objective with the just two modules, desirable because the railgun capacitors are actually divided into two 7.5 mF banks.

The simplest way to meet the objective with just two modules would be to add four more batteries to the bank. A much better way would be to reclaim residual energy from the railgun after firing so that the bank does not have to charged from zero. As shown in Fig. 8., the charger is very inefficient at low voltages. So, starting the charge cycle from 500 V or so could easily reduce the charge time by 25 ms or more.

Another technique under consideration is variable switching frequency. At low voltage a low frequency is better because the currents are higher and so switching losses are highest. This is possible because the transformer core takes longer to saturate at lower voltage. Also, higher frequencies should be possible at higher voltages when the currents are lower. As seen in Fig. 8., the output power is much lower at low and high output voltages. Variable switching frequency will hopefully increase average output power close to 70 kW. This, combined with the reclaiming of residual energy, may allows to meet the objectives with the current size bank.

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